13.—The origin of amphibolite and basic granulite bands in Precambrian gneisses of the south coast of Western Australia

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Abstract.
Evidence provided by chemical variation trends and by field associations suggests that amphibolite and basic granulite bands in the Precambrian gneisses of the south coast of Western Australia have probably been derived from extrusive or intrusive basic igneous rocks, rather than calcareous or dolomitic shales.

Introduction

Precambrian gneisses with roughly east-west tectonic trends outcrop along the south coast of Western Australia between Point D'Entrecasteaux and Israelite Bay. These rocks are intruded by numerous syn- and late-kinematic granitic plutons also of Precambrian age (Turek and Stephenson 1966), and form part of the Albany-Esperance Block, an arcuate belt wrapped around the southern and southeastern margins of the Archaean Yilgarn Block. The gneisses are predominantly granitic in character, with intercalated basic, pelitic, and minor calc-silicate bands. Migmatitic types are common. The metamorphic grade varies from upper amphibolite to lower granulite facies. Granulite facies rocks from the Fraser Range, at the northeastern end of the Albany-Esperance Block, gave a Rb-Sr age of 1330 ± 15 m.y. (Compston and Arriens 1968, p. 565) and this could be the age of the main metamorphism throughout the Block.

Bands and lenses of amphibolite (hornblende-plagioclase rocks) and basic granulite (hornblende-plagioclase-pyroxene rocks) are common throughout the south coast gneisses.

It is generally recognised that amphibolite and basic granulite may result from the metamorphism of various rock types including extrusive and intrusive basic igneous rocks, basic tuffs, and calcareous or dolomitic shales. The problem of distinguishing between meta-igneous and metasedimentary amphibolites and basic granulites has concerned geologists for many years. The only published study of the amphibolites and basic granulites of the south coast is by Clarke *et al.* (1954) who concluded (p. 54), from a comparison of major element compositions, that they were probably derived from basic igneous rocks. Since publication of this reconnaissance study it has become widely accepted that similarity in major element composition does not necessarily prove derivation from a basic igneous parent and various other approaches to the problem have been tried (e.g., Walker *et al.* 1960; Leake 1964; Shaw and Kudo 1965). It is the purpose of this paper to re-examine the problem of the origin of the amphibolite and basic granulite bands in the south coast gneisses in the light of recent information.

Methods

Seven samples of amphibolite and basic granulite have been analysed for 13 major and 13 trace elements. SiO_2, Al_2O_3, total Fe as Fe_2O_3, MgO, CaO, K_2O, TiO_2, P_2O_5, and MnO were determined by X-ray fluorescence spectroscopy using the techniques for sample preparation and matrix corrections described by Norrish and Hutton (1964, 1969). Seven synthetic standards were used for calibration, and standard rocks G-2, GSP-1, AGV-1, BCR-1, PCC-1, and DTS-1 were analysed to check the accuracy of the method. FeO was determined by titration against standard ceric sulphate solution, and Na_2O by flame photometry. Total water (H_2O^+ + H_2O^-) was estimated as the ignition loss, with a correction (based on the residual FeO contents of the ignited samples) applied for oxidation of FeO. H_2O^- was determined by drying the samples at $110°C$. The precision of the analyses at the concentration levels encountered was, with 95% confidence, about $\pm1\%$ of the amount present for SiO_2, Al_2O_3, total Fe as Fe_2O_3, FeO, CaO, K_2O, and TiO_2, and $\pm5\%$ of the amount present for MgO, Na_2O, P_2O_5, MnO, and H_2O^+.

Co, Rb, Sr, Y, Zr, Ba, La, Pb, and Th were determined by X-ray fluorescence spectroscopy using pressed powder samples (Norrish and Hutton 1964; Norrish and Chappell 1967, p. 205). Standard rocks W-1, G-2, GSP-1, AGV-1, BCR-1, PCC-1, and DTS-1 were used for calibration, and the procedure of Hower (1959) was used for matrix corrections. Interferences by $FeK\beta_1$ in Co analyses, $RbK\beta_{1,3}$ in Y analyses, and $SrK\beta_{1,3}$ in Zr analyses were compensated by mathematical corrections based on measurements on samples spiked with known concentrations of the interfering element (Leake *et al.* 1969, p. 63). Li, Ni, Cu, and Zn were determined by atomic absorption spectroscopy. The precision of the analyses at the concentration levels encountered was, with 95% confidence, roughly $\pm5\%$ of the reported concentration for Ni, Zn, Rb, Sr, Zr, and Ba; $\pm10\%$ for Li, Co, and Y; $\pm15\%$ for Cu, La, and Pb. Th was not detected.

Modes were determined by counting 1000 points over a sample area of about 500 mm[2] Plagioclase compositions were estimated from measurements of the extinction angle $X^1 \wedge 010$ in sections perpendicular to x (Deer *et al.* 1963, Vol. 4, Fig. 55), orthopyroxene compositions

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Table 1

Chemical analyses, C.I.P.W. norms, Niggli values, and modes for amphibolites (analyses 1–5) and basic granulites (analyses 6–11) from the south coast of Western Australia. Average abundances of major elements (Mawson 1967, Table VI) and trace elements (Prinz 1967, Table II) for tholeiites (column 12) and alkali basalts (column 13) are listed for comparison

Chemical analyses

	Amphibolite					Basic granulite						Comparison	
	1 (54556)	2 (54562)	3 (54563)	4 (65581)	5 (32613)	6 (—)	7 (16582)	8 (20015)	9 (56601)	10 (56603)	11 (56612)	12 (—)	13 (—)
SiO_2	55·42	49·95	48·95	51·76	50·02	49·99	46·76	48·14	55·71	49·94	49·27	51·2	47·2
Al_2O_3	16·82	15·45	15·05	16·88	12·98	18·35	17·94	14·72	16·06	12·49	15·63	15·9	15·8
Fe_2O_3	1·40	3·19	2·83	4·97	2·75	2·15	3·16	1·93	1·09	1·47	1·91	2·9	3·2
FeO	6·46	8·31	8·06	6·16	12·16	5·97	8·78	12·92	8·80	12·80	10·48	8·0	8·0
MgO	4·82	6·60	8·33	4·56	6·16	6·19	8·84	6·78	2·46	8·03	5·17	6·2	7·0
CaO	7·60	8·04	9·39	7·22	10·13	10·30	10·22	5·53	6·57	8·35	8·17	9·9	10·1
Na_2O	3·00	2·50	2·90	2·64	2·04	3·79	2·97	2·26	4·50	2·84	4·00	2·4	3·2
K_2O	1·89	1·45	1·50	2·44	0·44	0·91	1·46	0·35	1·89	1·02	1·97	0·7	1·4
H_2O^+	1·15	1·52	1·52	1·10	1·72	0·92	0·64	0·68	0·48	0·95	1·15	0·8	1·0
H_2O^-	0·16	0·14	0·14	0·16	0·03	0·28	0·04	—	0·17	0·17	0·11	—	—
TiO_2	0·89	1·06	0·88	1·51	1·42	0·87	0·93	1·44	1·21	0·67	1·57	1·6	2·4
P_2O_5	0·22	0·30	0·27	0·56	0·20	0·30	0·23	0·19	0·57	0·11	0·57	0·21	0·48
MnO	0·22	0·48	0·28	0·23	0·29	0·14	0·18	0·24	0·28	0·43	0·27	0·17	0·16
Total	100·17	99·97	99·90	100·19	100·46*	100·48**	100·15	100·18	100·39	99·27	100·27		

Trace Elements (p.p.m.)

	1	2	3	4	5	6	7	8	9	10	11	12	13
Li	16	21	28	24					8	19	36	10	12
Co	32	36	50	34					16	37	39	39	42
Ni	86	88	137	80					56	149	66	85	101
Cu	10	8	43	59					17	8	7	127	108
Zn	100	180	108	134					171	288	166		
Rb	136	104	86	137					38	38	92	30	51
Sr	487	264	228	570					364	172	494	450	774
Y	25	48	31	36					73	23	35	32	30
Zr	86	146	81	185					461	69	157	108	138
Ba	491	599	198	929					2101	490	696	244	444
La	33	39	13	36					72	18	46		
Pb	31	17	17	20					20	16	18		
Th	<5	<5	<5	<5					<5	<5	<5		

C.I.P.W. Norms (wt. %)

	1	2	3	4	5	6	7	8	9	10	11	12	13
q	5·42	—	—	5·13	2·99	—	—	—	1·86	—	—		
or	11·15	14·75	8·87	14·43	2·62	5·56	8·90	2·07	11·18	6·02	11·65		
ab	25·38	21·15	24·53	22·33	17·26	29·13	17·29	18·86	38·07	24·02	27·52		
an	26·94	23·57	23·62	26·99	21·96	30·51	30·86	29·19	19·67	18·38	18·87		
ne	—	—	—	—	—	1·56	4·26	—	—	—	3·42		
di	8·04	11·77	17·23	4·20	19·98	15·51	15·46	1·67	7·81	18·56	14·90		
hy	17·69	12·67	0·83	14·45	23·66	—	—	18·50	15·91	12·85	—		
ol	—	7·12	16·73	—	—	11·40	15·82	17·84	—	14·63	15·55		
mt	1·68	2·01	1·67	2·86	2·69	1·67	1·82	2·78	2·30	1·26	2·98		
il	2·02	4·62	4·10	7·21	3·98	3·13	4·64	2·74	1·58	2·13	2·76		
ap	0·51	0·70	0·63	1·31	0·46	0·67	0·34	0·34	1·34	0·25	1·35		

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Niggli Values

al	27·5	22·0	20·1	26·4	18·0	25·6	23·2	19·3	28·5	16·8	22·3
fm	38·3	47·4	44·7	42·1	51·1	37·8	44·3	50·3	35·0	55·1	44·0
c	22·8	20·8	22·8	20·5	25·6	26·5	24·1	25·1	20·4	20·4	21·2
alk	11·4	9·7	8·5	10·9	5·4	10·1	8·4	5·3	16·1	7·8	12·5
mg	0·56	0·57	0·64	0·55	0·43	0·58	0·51	0·45	0·32	0·51	0·46

Modes (vol. %)

Quartz	12·6	0·2		0·6	A				10·7		
K-feldspar	2·8	4·7			M	M	M		55·6		
Plagioclase	52·4	30·0	29·7	43·5	M	A	M	M	1·7	31·0	42·9
Biotite	20·7	25·3	21·3	13·0		M	M		15·8	6·5	16·6
Hornblende	10·3	39·8	58·4	41·2	M	M	M	M	13·4	37·5	28·7
Orthopyroxene						M	M	M		20·2	2·3
Clinopyroxene					M			M			
Sphene	0·4	tr	tr	0·3	A	A	A	A		tr	0·1
Opaques	0·3	tr	0·1	1·2	A	A	A	A	1·3	tr	tr
Others	0·5	tr	tr	0·2							

Optically Determined Mineral Compositions

Plag. An%	37	37	38	44–46	35	40	50	50	35	37	34
Opx. Fe%								53	75	57	63
Cpx. Ca:Mg:Fe										44:36:20	39:26:35

Analyses 5–8 are quoted from Clarke *et al.* (1954. Table IV).
* Includes 0·03% CO_2; 0·06% FeS_2. ** Includes 0·09% FeS_2; 0·12% Cl: 0·05% Cr_2O_3.
M—Major constituent.   A—Accessory.
Specimen numbers refer to the collection of the Geology Department, University of Western Australia.

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from measurements of refractive index γ (Deer et al. 1963, Vol. 2, Fig. 10), and clinopyroxene compositions from measurements of $2V_z$ and refractive index β (Deer et al. 1963, Vol. 2, Fig. 41).

Description of the Amphibolites and Basic Granulites

The amphibolite and basic granulite bands range in thickness from less than one metre up to several tens of metres, and are normally conformable with foliation and lithological banding in the surrounding gneisses. One notable exception occurs near Doubtful Island Bay where a discordant band of basic granulite clearly of intrusive igneous origin is well exposed. However, the great majority of basic bands could be interpreted as sedimentary or tuffaceous layers, or as igneous flows or sills.

Most of the basic bands are broadly homogeneous, but some are thinly layered suggesting either metamorphic differentiation or original (sedimentary?) layering. Recrystallisation during metamorphism has completely destroyed original textures, producing granoblastic or foliated fabrics. Hence the parent rock must be deduced from the present chemical composition. In this approach it is necessary to make the assumption, though difficult to substantiate, that metamorphism was isochemical (except for volatiles).

The 11 rock analyses on which this study is based comprise 4 previously presented by Clarke et al. (1954, Table IV) and 7 new analyses carried out by the author. The 11 analysed samples are from 5 widely separated localities (Torbay, Albany, Cape Riche, lower Pallinup River, and Point Irby; see Fig. 1) spanning a total distance of 130 km. The samples include representatives of the amphibolite facies and the amphibolite-granulite transitional facies, and cover all the more common variations in mineral assemblage. Samples showing evidence of metasomatism (usually granitisation; less commonly carbonation or scapolitisation) or of significant retrogression have been carefully excluded from the study.

Chemical analyses, C.I.P.W. norms, Niggli values, and modes for the samples studied are listed in Table 1. There appear to be no consistent differences in major element composition, except perhaps water content, between the amphibolite and basic granulite samples. Hence the basic granulites are believed to be the higher-grade equivalent of the amphibolites. This belief is supported by the fact that these two rock types are generally not associated in the field.

Discussion

It is evident in Table 1 that the analysed samples are similar in major and trace element composition to average tholeiite and alkali basalt (Manson 1967; Prinz 1967). Following the system of Yoder and Tilley (1962, p. 352), four of the analysed samples may be classified as oversaturated tholeiite (normative quartz and hypersthene), four as undersaturated tholeiite (normative hypersthene and olivine), and three as alkali basalt (normative olivine and nepheline).

However, bulk chemical similarity to basic igneous rocks does not prove an igneous origin. Most authors accept that mixtures of carbonate and shale in appropriate proportions may, after high-grade metamorphism with loss of volatiles, closely resemble basic igneous rocks in bulk composition. Attempts (e.g., by Evans and Leake 1960; Walker et al. 1960) to distinguish between meta-igneous and metasedimentary
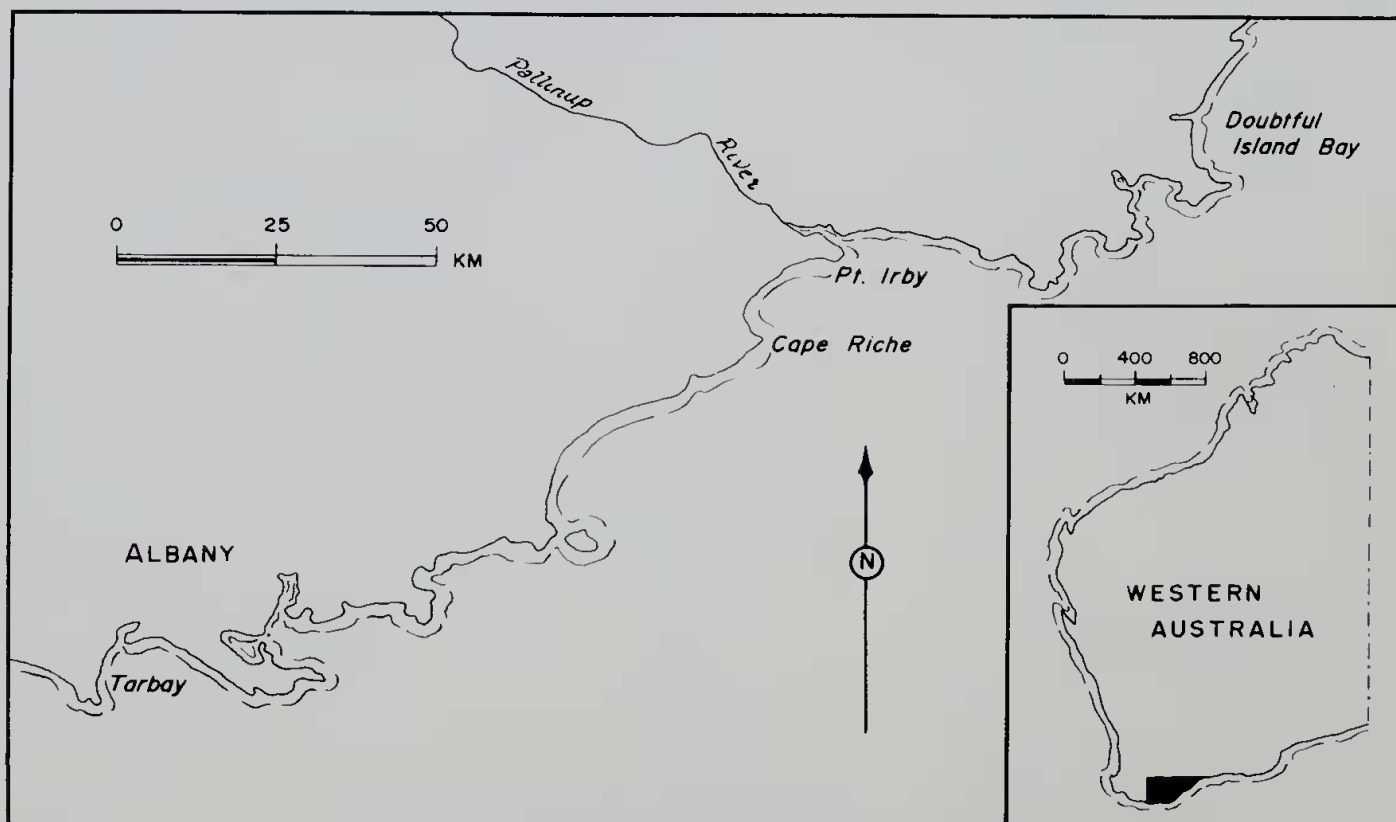

Figure 1.—Locality map.

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amphibolites on the basis of abundance levels of certain trace elements have not produced completely diagnostic criteria because observed ranges of trace element concentrations in basalts and in carbonate-shale mixtures greatly overlap.
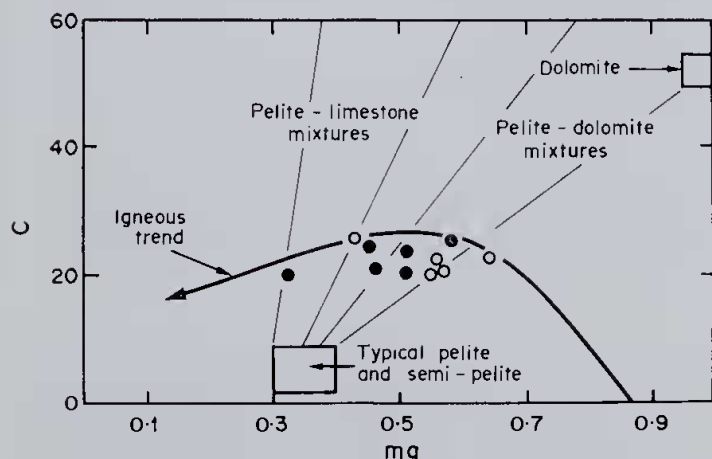

Figure 2.—Niggli c-mg plot for south coast amphibolites (circles) and basic granulites (dots) (after Leake 1964).
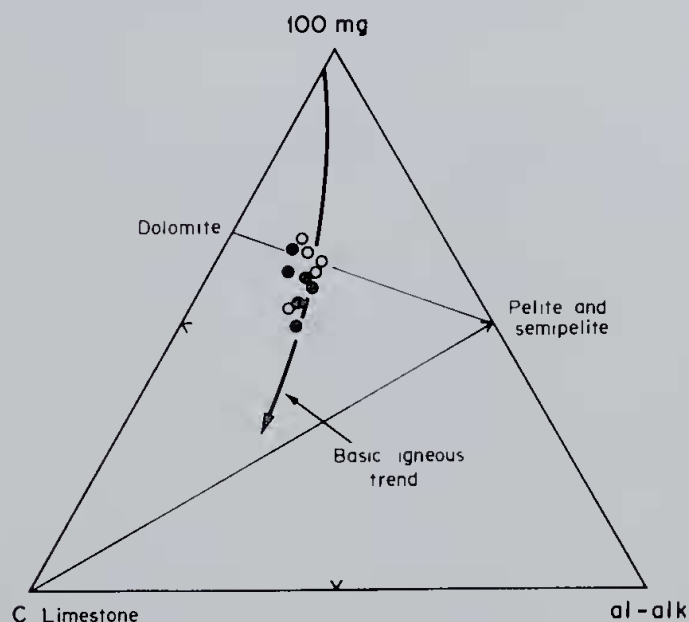

Figure 3.—100mg-c-(al-alk) plot for south coast amphibolies (circles) and basic granulites (dots) (after Leake 1964).

However, Leake (1964) has suggested that chemical variation trends in suites of samples, rather than absolute abundance levels, may be significant, and this approach is followed here. Perhaps 11 analyses are insufficient to reliably define variation trends, but nevertheless some interesting results emerge. Niggli c-mg and 100mg-c-(al-alk) plots of the south coast amphibolites and basic granulites (Figs. 2 and 3, after Leake 1964) closely follow igneous trends, and Ni and Co concentrations appear to increase with increasing Niggli mg values (Figs. 4 and 5) as expected in igneous rocks, but not in carbonate-shale mixtures (Leake 1964). Therefore derivation of the amphibolite and basic granulite bands in the south coast gneisses from extrusive or intrusive basic igneous rocks, or possibly basic tuffs, seems likely.
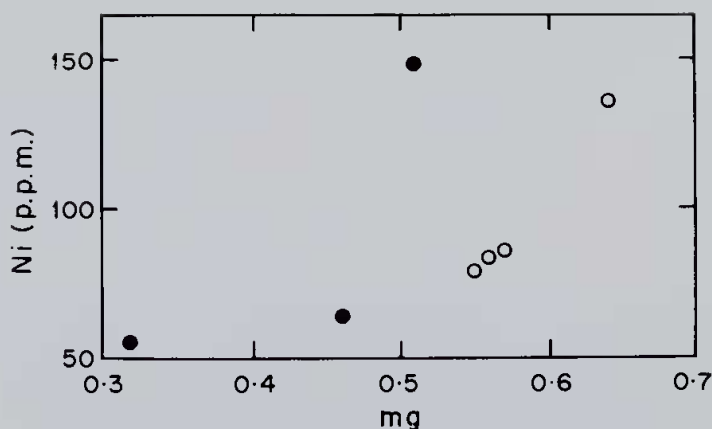
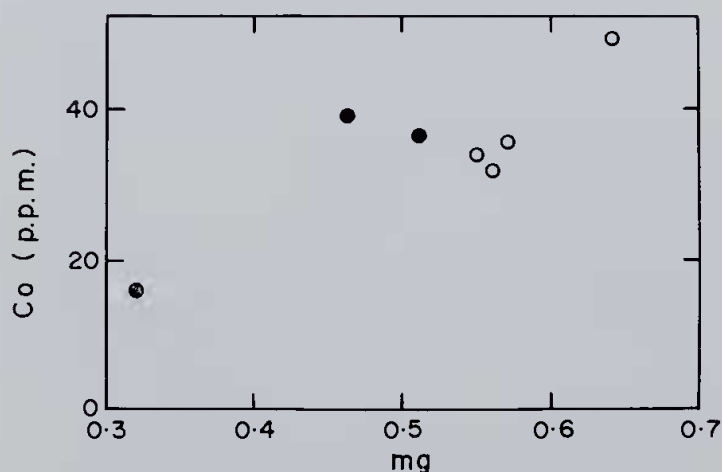Figure 4.—Ni-mg plot for south coast amphibolites (circles) and basic granulites (dots).

Figure 5.—Co-mg plot for south coast amphibolites (circles) and basic granulites (dots).

However, Orville (1969) has demonstrated that rocks composed largely of hornblende and plagioclase, with relatively small amounts of other minerals, must plot in a limited field along the hornblende-plagioclase tie-line on the ACF diagram, and hence approximate the field of basic igneous rocks (see Fig. 6, after Orville 1969). A consideration of the chemical compositions of hornblende and plagioclase leads to the conclusion that most amphibolites must also plot within the field of basic igneous rocks on c-mg and 100mg-c-(al-alk) diagrams. Orville (1969) has also shown that hornblende-plagioclase rocks can, because of their restricted bulk compositions, represent only a very limited composition range in carbonate-shale mixtures (see Fig. 6). Therefore it can be argued that hornblende-plagioclase rocks, regardless of their origin, might be expected to approximate basic igneous rocks in major element composition, and might be expected to show igneous, rather than sedimentary, trends on variation diagrams based on major element composition.

Because mixtures of carbonate and shale are unlikely to be confined to the restricted range of proportions which yields amphibolite on metamorphism (shale with 20-40% dolomite; see Orville 1969, Fig. 5), it follows that amphibolites derived from carbonate-shale mixtures are likely to be intimately associated in the field with calc-silicate rocks (e.g., plagioclase-diopside grossular rocks) and pelitic gneisses (e.g.,

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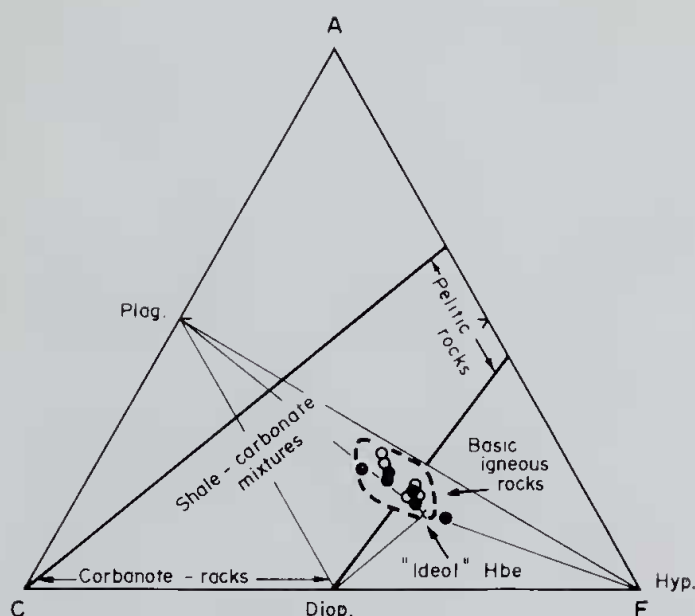
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Figure 6.—ACF plot for south coast amphibolites (circles) and basic granulites (dots) (after Orville 1969).

quartz - plagioclase - garnet - biotite - cordierite gneisses), and transitional assemblages. Associations of this type, though not unknown, are uncommon in the south coast gneisses; the amphibolite and basic granulite layers are normally interbanded with granitic gneiss. Furthermore, lithologies representing bulk compositions transitional between amphibolite and pelitic gneiss and between amphibolite and calc-silicate rock are rare in the region in question, so there does not appear to be a continuous variation from calc-silicate to pelitic rock through amphibolite and basic granulite. The amphibolite and basic granulite appear to represent a distinctly defined rock type rather than an intermediate member of a carbonate-shale-derived series. The lack of close association in the field between calc-silicate rocks, amphibolites, and pelitic gneisses also rules out Orville's (1969) model for the genesis of metasedimentary amphibolites involving chemical reaction between adjacent incompatible carbonate and pelitic assemblages.

Conclusions

It is concluded that amphibolite and basic granulite bands in the gneissic complex of the south coast of Western Australia have been derived mainly from extrusive or intrusive basic igneous rocks rather than calcareous or dolomitic shales because:

(i) they follow igneous trends on c-mg, 100mg-c-(al-alk), Ni-mg, and Co-mg variation diagrams;

(ii) they are not usually closely associated in the field with calc-silicate and pelitic gneisses.

Derivation from an igneous parent is further supported by the occurrence at Doubtful Island Bay of at least one band of basic granulite showing discordant, clearly intrusive relations with surrounding rocks. However, the possibility that the parent rocks were basic tuffs cannot

be ruled out in the absence of relict textures, but this is perhaps unlikely in view of the general scarcity of basic tuffs in the geologic column.

References

Clarke, E. de C., Phillipps, H. T., and Prider, R. T. (1954).—The Pre-Cambrian geology of part of the south coast of Western Australia. *J. Roy Soc. W. Aust.* 38: 1-64.

Compston, W. and Arriens, P. A. (1968).—The Precambrian geochronology of Australia. *Canad. J. Earth Sci.* 5: 561-583.

Deer, W. A., Howie, R. A., and Zussman, J. (1963).—"Rock-Forming Minerals", Vols. 1-5. Longmans, London.

Evans, B. W. and Leake, B. E. (1960).—The composition and origin of the striped amphibolites of Connemara, Ireland. *J. Petrol.* 1: 337-363.

Hower, J. (1959).—Matrix corrections in the X-ray spectrographic trace element analysis of rocks and minerals. *Amer. Min.* 44: 19-32.

Leake, B. E. (1964).—The chemical distinction between ortho- and para-amphibolites. *J. Petrol.* 5: 238-254.

Leake, B. E., Hendry, G. L., Kemp, A., Plant, A. G., Harvey, P. K., Wilson, J. R., Coats, J. S. Aucott, J. W., Lünel, T., and Howarth, R. J. (1969).—The chemical analysis of rock powders by automatic X-ray fluorescence. *Chem. Geol.* 5: 7-86.

Manson, V. (1967).—Geochemistry of basaltic rocks: major elements. In "Basalts". (H. H. Hess and A. Poldervaat, eds.) 215-269. John Wiley, New York.

Norrish, K. and Chappell, B. W. (1967).—X-ray fluorescence spectrography. In "Physical Methods in Determinative Mineralogy". (J. Zussman, ed.), 161-214. Academic Press, London.

Norrish, K. and Hutton, J. T. (1964).—Preparation of samples for analysis by X-ray fluorescent spectrography. *Divl. Rept. Div. Soils CSIRO* 3/64.

Norrish, K. and Hutton, J. T. (1969).—An accurate X-ray spectrographic method for the analysis of a wide range of geological samples. *Geochim. Cosmochim. Acta* 33: 431-453.

Orville, P. M. (1969).—A model for metamorphic differentiation origin of thin-layered amphibolites. *Amer. J. Sci.* 267: 64-86.

Prinz, M. (1967).—Geochemistry of basaltic rocks: trace elements. In "Basalts". (H. H. Hess and A. Poldervaart eds.) 271-323. John Wiley: New York.

Shaw, D. M. and Kudo, A. M. (1965).—A test of the discriminant function in the amphibolite problem. *Min. Mag.* 34: 423-435.

Turek, A. and Stephenson, N. C. N. (1966).—The radiometric age of the Albany Granite and the Stirling Range Beds, south-west Australia. *J. Geol. Soc. Aust.* 13: 449-456.

Walker, K. R., Joplin, G. A., Lovering, J. F., and Green, R. (1960).—Metamorphic and metasomatic convergence of basic igneous rocks and lime-magnesia sediments of the Precambrian of northwestern Queensland. *J. Geol. Soc. Aust.* 6: 149-178.

Yoder, H. S. and Tilley, C. E. (1962).—Origin of basalt magmas: an experimental study of natural and synthetic rock systems. *J. Petrol.* 3: 342-352.

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